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On the Emergence of Sociotechnical Regimes of Electric Urban Water Transit Systems

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Abstract: Urban activities, including urban mobility, play a crucial role in climate change mitigation. Urban mobility is currently at a crossroads. In a business as usual scenario, CO_2 emissions from urban transportation will grow by one fourth by 2050. Nevertheless, during this period, it may drop by about one third. To make the drop happen, we need to introduce comprehensive policies and measures. Electrifying urban transit is one feasible solution. This study investigates whether and how urban water transit systems have been electrified—a means of transport which has not been well researched in this respect. A multilevel perspective and the comparative case study method were employed to answer the research questions. The comprehensive study focussed on 24 cities representing the current experience in planning and operating water transport, based mainly on secondary, primarily qualitative, data, such as industry reports, feasibility studies, urban policies, and scientific papers. The primary outcome is that urban electric passenger ferries left their market niches and triggered a radical innovation, diffusing into mainstream markets. However, urban diversity results in various paths to electrification, due to the system's physical characteristics, local climate and transport policies, manufacturing capacity, green city branding, and the innovativeness of international ferry operators. Three dominant transition pathways were identified—a comprehensive carbon neutral policy, a transport sector policy, and a research and development policy. From a multilevel perspective, cities can be considered a bridge between niches and regimes that provide the actual conditions for implementing sociotechnical configurations.

Keywords: transport electrification; urban transit system; sociotechnical regime; electric ferry; hybrid diesel–electric ferry; carbon neutrality

Citation: Tarkowski, M. On the Emergence of Sociotechnical Regimes of Electric Urban Water Transit Systems. *Energies* **2021**, *14*, 6111. https://doi.org/10.3390/en14196111

Academic Editor: Victor Manuel Ferreira Moutinho

Received: 31 July 2021
Accepted: 22 September 2021
Published: 25 September 2021

1. Introduction

Despite an increasing awareness of the limits to growth [1,2] and the sudden anthropogenic climate change that is its manifestation, efforts to mitigate the genuinely unsustainable way humankind exists seem far from satisfactory [3]. The research on sustainability transitions explains why this shift is difficult to implement. The efforts that focus on incremental improvements and technological solutions are insufficient. A radical shift, to new kinds of sociotechnical systems consisting of "sustainable transitions," is required [4]. This article investigates a shift in one of the most prominent sociotechnical systems—the urban passenger transport system. Chen and Kauppila [5] estimated in 2015 that this system, limited to cities of over 300,000 people, covers 37% of the global CO_2 emissions from passenger transport, and 20% of the entire transport sector. Their modelling outcomes suggest that urban mobility is at a tipping point. In the business as usual scenario, CO_2 emissions will increase by 27% by 2050. However, between 2015 and 2050 mixed policies—rigorous pricing strategies or integrated land use and transport planning—may reduce the carbon intensity of travel by 35%. Experience so far shows how difficult this challenge is to achieve. However, while an increase in energy efficiency has given some benefits, it may also generate a rebound effect—an increase in transport activity [6]. Moreover, the carbon impacts of urban mobility plans are often neglected or underestimated [7]. Therefore, a reduction in transport activity is necessary, but technological pathways of reducing CO_2 intensity must also be taken into account [5]. One of the most promising and mature pathways is to implement electric propulsion systems in public transport modes [8]. An extensive systematic literature review [9] proved that urban experiments with low carbon public transport mainly focus on low emission vehicles [10–13] and rapid bus transit systems [14–18]. This paper fills a research gap, implementing electric propulsion into urban water transit systems. Despite the proportion of ferry transport usually being low in cities with extensive public transport systems [19], electrification is one of the steps to decreasing the carbon intensity of these systems. Moreover, ferry shipping, predominantly urban and coastal, is the leading training ground for decarbonising maritime transport. Short trip distances and a small and permanent number of harbours allow energy storage systems with sufficient capacity to be used, and relevant charging facilities to be built [20].

The International Maritime Organisation, following the recommendation of the United Nations Framework Convention on Climate Change expressed in the Kyoto Protocol (1992) and the Paris Agreement (2015), have taken actions towards decarbonising the maritime sector [21]. In addition, regional entities such as the European Union support this process [22]. According to a multilevel perspective [23]—the framework adopted in this article for the sustainable transition analysis—all these macroscale activities constitute a sociotechnical landscape. The change itself takes place in the mesoscale, within the sociotechnical regimes. Urban areas are an arena for transforming these regimes and, more broadly, one of the main areas for reducing emissions [24]. Transformation is stimulated not only by top down processes, but also by bottom up ones. Regimes derive technical, societal, and organisational solutions from niches. Creativity is also the domain of cities. It is not only about technological progress, but about the ability to mobilise local communities to solve the most important global problems [25–27], including limiting the scale and effects of global warming [28,29]. The analysis of cities in the context of electrifying ferry shipping seems more promising than in systems serving more extensive areas.

Changes in transport are a noticeable part of climate change adaptation research [30,31]. However, the issue of urban water transit systems remains outside the mainstream [9]. The relevant scientific literature set employing a multilevel approach has only been growing for a few years, and remains limited. The work most relevant to this subject is by Anwar et al. [20]. Comprehensively, it describes the status and prospects of decarbonising ferry shipping, but not only for urban water transit. However, it argues that pure electric propulsion systems are developed mainly on harbour waters, while hybrid–electric dominates in coastal ferry shipping. The authors also identified challenges and emerging trends: the technical, operational, and legislative. In turn, Tarkowski [32] identified the main electrification drivers of ferry shipping by analysing four different case studies, including a typically urban one—Amsterdam. He identified four factors: natural and anthropogenic environmental features, electromobility policy, local design, and manufacturing capacity. Several papers have also been published in the last two years on the technical, socioeconomic, and environmental conditions for implementing electric or hybrid ferries in selected individual cities or urban regions [33–37]. Works on urban ferry systems provide a broader context for the issue, although not necessarily focussing on electrification [19,38–42]. On the other hand, the articles devoted to the electrification of the entire shipping industry [20,21,43,44] treat the issues of urban passenger shipping marginally.

The above literature review indicates a research gap in the electrification of urban ferry systems, analysed from the sociotechnical perspective. The electrification of this shipping segment is relatively easy, based on existing technologies, and is progressing steadily. This article aims to answer two fundamental questions: The first question concerns the degree of the electrification of water transit systems and the technical and organisational innovations applied. The answer allows the status of the decarbonisation of urban water transit systems to be assessed. In terms of a multilevel analysis, this estimates the degree of the shift in sociotechnical regimes towards electromobility. The second question concerns the conditions and factors of transition paths. The answer identifies repetitive patterns, especially those that have proven to be effective. It also reveals atypical solutions that are well suited to the conditions of individual cities.

The structure of the article reflects the logic of the research procedure. The next section outlines the history of the development and the main types of electric propulsion systems, their main technical and operational benefits, and the limitations of their use. Then, the research methods and sources are discussed. The results part of the study reports the advancement of the electrification of ferry systems and the main factors driving this process. The discussion embeds the results in a broader research context, indicating their contribution to scientific knowledge. The article ends with conclusions, including research limitations and indications of directions for further research.

2. Applications of Electric Propulsion Systems on Ships

The use of electric propulsion systems to propel vessels has a long history, dating back to 1835 [45]. Due to its very low energy density, this kind of propulsion lost the competition in merchant and passenger shipping to steam and, then, the diesel engine and heavy fuel oil, which offer many times the power and travel range. However, even ships driven by diesel engines require generators to produce the electricity (Figure 1A) necessary to power critical marine equipment (machinery, electrical equipment, and lighting). A blackout is a hazardous incident for shipping safety [46]. In order to improve propulsion systems' redundancy, several electrical generators are usually installed on each ship. Installing azimuth thrusters or azipods to increase ship manoeuvrability ushered in a renaissance of using electricity to propel ships. Systems for transmitting electrical energy from the generator to an electric motor (Figure 1B) proved more straightforward to build and operate, more reliable, and more space-saving in engine rooms. This kind of propulsion system is also widespread on ferry vessels and, in the case of larger ferries, is available for retrofitting [20].

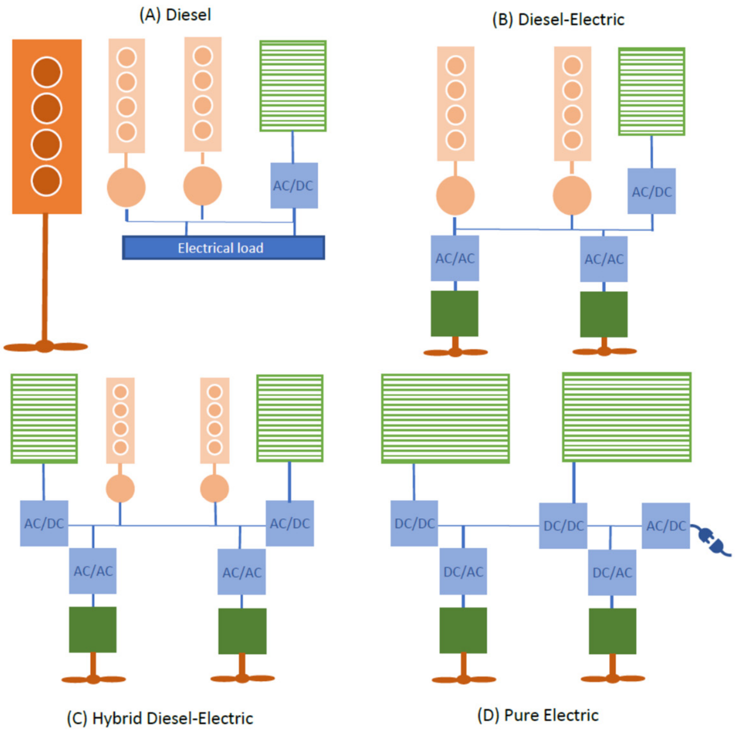

Figure 1. Basic mechanical, hybrid, and pure electric vessel propulsion systems based on electrochemical energy sources.

The main idea of hybrid diesel–electric vessel propulsion systems (Figure 1C) is to ″shave the peak″—to ensure that additional power to electric motors during energy-consuming manoeuvres comes from the batteries, instead of increasing the power output of the diesel generators. The batteries are loaded when a vessel moves at optimum cruising speed. The maximum power of the generators in hybrid diesel–electric systems is lower than in diesel main engines or diesel–electric systems, but it requires much larger batteries. However, pure electric systems have not been equipped with generators (Figure 1D). They need even larger batteries and an onshore charging infrastructure. In practice, the intermediate systems—i.e., plug in hybrid diesel–electric systems—are also used.

Batteries are not the only kind of energy storage system. Fuel cells are another type of chemical energy storage. As the following argumentation proves, both solutions have been applied in the case of urban ferry vessels. Several alternative technologies are based on electrical (superconducting magnetic energy storage or ultracapacitors) or mechanical (flywheel) energy [47]. The application of these systems is marginal—they were not found in the analysed cases; therefore, they were omitted from the article.

From a sustainability transition point of view, the main advantage of introducing electric propulsion systems is the reduction in greenhouse gasses (GHG) and other pollutions emitted by ferries, at least in the area of exploitation. The extent to which electrification can reduce the total national or global emissions and can diminish the pressure on nonrenewable energy resources depends, in general, on the types of primary energy production, the distribution system, and the availability of renewable energy sources [48]—in particular, on the local conditions for producing and providing electricity from renewable sources. These questions are crucial for sustainability transition to succeed, but are beyond this article's scope. In addition, excluding GHG emissions related to production, the potential reduction in CO_2 emissions from a shipping fleet with a hybrid-electric propulsion system can be from 33% to 77% [49]. Pure electric ferries are zero emission in operation areas. The environmental impact of shipping is not limited to atmospheric conditions—the bottom substrate and habitats, foreshore, aquatic biota, and physicochemical water properties are also under pressure from shipping [50]. The development of electric propulsion systems can reduce the pressure from the risk of oil spills, and noise and vibrations from engines, propellers, or thrusters.

The electrification of ferry shipping increases marine safety (propulsion redundancy and ship reliability) and brings more economic advantages. Liebreich et al. reported that for Latin America [51] the total undiscounted costs over a 30-year lifetime are approximately 25% higher for a diesel powered ferry than a pure electric ferry. It is a question of the difference in fuel and electricity prices, and savings in maintenance and crew costs. Electric ferries admittedly require costly battery replacement, but a major engine overhaul is not necessary. Likewise, the capital costs for an electric ferry are almost 25% higher, mainly due to the port infrastructure and electrical connection fee. Some authors have also argued that the expected growth in battery energy density, significant decline in battery prices, and improvements in vessel construction will make pure electric ferries more competitive. The maximum operational range will increase from about 40 km in 2020 to above 80 km, in twenty years. The frequency of cruises will also double.

3. Materials and Methods

A comparative case study is the leading research method, the outcomes of which are referred to in this article. It is a qualitative tool effectively used in various fields of social science research to investigate the impact of policy and practice [52]. The method is also widely adopted in urban and regional studies [53]. Due to these two premises, it can be helpful in investigating the transformation of sociotechnical regimes. However, scholars call for more process orientated and rigorous comparative case studies [52,54–56]. Krehl and Weck [53] summarised this critique, and argued that a more recent approach should treat cases as space specific, emergent and interconnected, whereas the process of comparison should be repetitive and process centred, and should seek differences and include diverse experiences. This study is based on a multilevel perspective precisely because of its adequacy to the analysed problem. Krehl and Weck also discussed the minimum standards for comparative case study research regarding the theoretical framework, the objective of comparison, the case study selection strategy, potential trade offs, and ways of generalisation [53].

The theoretical framework has already been outlined—it is a multilevel perspective employed to investigate sociotechnical system changes. The central assumption of this framework is that inventing a new technology is not enough to change societies. Changes in markets, user practices, policy, and culture are also indispensable. There are three levels of analysis involved in the multilevel perspective: niches, regimes, and landscapes [57]. The subject of the niche layer investigation is radical innovations. Niches develop the ecosystems of learning by doing, using, and interacting, and by building networks that support innovations. They are usually protected or insulated from the market rules established by dominant regimes. Due to the selection and retention mechanism, regimes incrementally adapt and develop the innovations invented in niches—the adaptation process is based on a" semi-coherent set of rules carried by different social groups. By providing orientation and coordination to the activities of relevant actor groups, sociotechnical regimes account for the stability of sociotechnical configurations" [23]. While the set of regimes' rules is rooted in communities, the sociotechnical landscape consists of external economic, political, cultural, and environmental factors. Examples of these factors are oil prices, intergovernmental agreements, or a growing awareness of the dangers to society from sudden, anthropogenic, global climate change.

The objects of this article's comparison are shifts in the sociotechnical systems of urban water transit under the emerging sociotechnical landscape of sustainability transition. The shift is understood as a recombination of the mutual interaction between the system's actors: ferry owners or operators; public transport authorities and municipal/metropolitan/regional authorities; financial, research, and supplier's networks; users; and societal groups. However, temporal and structural changes are not the only important factors. The locality and proximity can also help to explain "why and how change occurs in sociotechnical systems, and why it occurs in some places and not in others" [58]. Several studies have suggested [58–60] that cities or urban regions are the appropriate spatial scale for better understanding the nature of shifts in sociotechnical regimes. Hence, the spatial scope of the study is its set of cities or urban regions. The water transit systems under study are parts of urban transport systems. Therefore, cities—understood as functional urban areas—are the objects of comparison. However, the systems are not limited to city borders or managed by city authorities. The metropolitan or regional authorities were responsible for public transport in several cases. That is why the metropolitan or regional bodies were taken into account in the comparison.

The case selection strategy reflects the trade off between the profound contextualised study of a case, and a cross-case analysis (depth vs. scope) [53,56,61]. One practical limitation was the amount of qualitative secondary data analysis available via the Internet, which makes a thorough analysis of each case extremely difficult. Thus, a strategy based on the most varied case selection was initially applied, to highlight the scope of shifts inside sociotechnical regimes—the variety in the processes of ferry system electrification. The set of 23 urban ferry systems, from around the world, that was gathered by Cheemakurthy, Tanko, and Garme [19] was utilised in the study (Figure 2).

During the analysis, this was supplemented with one other system (Lisbon). As the authors said, "23 cities were chosen as part of this compilation, which represents the breadth of experience in planning and operating water transport currently available". The central categorisation was the overall scale of water transit systems based on the number of routes and passengers served. The variety of systems also includes route and service type, scheduling, transit network integration, terminal design, accessibility, comfort and public perception, vessel design, and operating costs [19]. The selection represents the trade off between scope and data availability. The limitation was online access to transit operators' official websites, transport planning policy or strategies, and technical reports published in English. Most of the selected cities are transparently governed by highly digitalised, democratic, and internationally cooperating authorities. Thus, the set is not fully representative of global systems. However, it is promising to investigate ferry electrification processes due to their adequate tangible and intangible resources. To ensure the depth–scope balance, the most promising cases—in terms of advances in ferry system electrification—were subjected to more detailed analysis. This allows significant or repeated phenomena, favourable to the introduction of electric propulsion on ferry vessels, to be identified.

As the above discussion suggests, the ambition of generalisation must be limited. However, there are possibilities to outline fundamental regularities: the first is assessing the degree of the proliferation of ferry vessel electric propulsion systems, assuming that the analysed systems are more susceptible to electrification; the second is identifying efficient and repetitive drivers of the shift toward electrification in the sociotechnical regimes responsible for ferry systems' performance.

The research procedure reflects the above mentioned assumptions and trade offs. The electrification process outcomes were identified in the first stage (Figure 3). The scope included ferry operators or owners—the core actors in the shift towards electrification (Appendix A). An investigation of their websites provided information on the actual degree of fleet electrification, and completed or planned investment. The operational factors—technical, economic, and geographic—of the systems' performance, due to their impact on electrification's price/performance dimension, can also be found in the research agenda. Sometimes, ferry vessels are connected with urban/corporate brands or landmarks; the symbolic meaning may foster fleet electrification. The research extension regarding charging/fuelling infrastructure, passenger facilities, maintenance, and investment issues took place in the second stage. The third stage consisted of strategic questions, such as rules, financial incentives, emission standards, investment plans, and the preferred direction of modal split changes. The investigation focussed mainly on official documents: transport strategies or mobility plans (Appendix B).

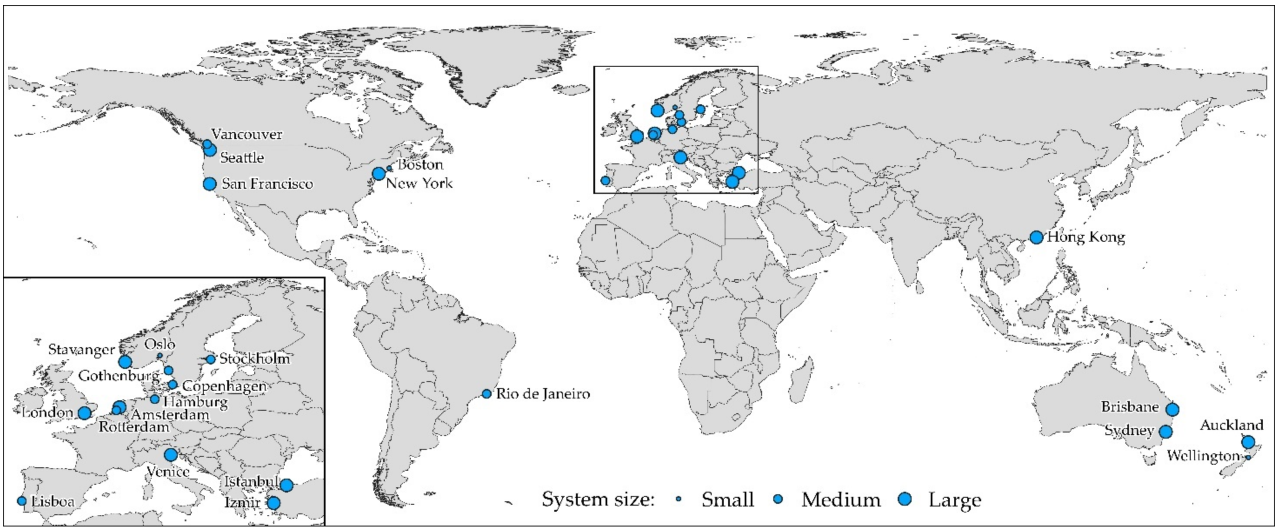

Figure 2. Location of analysed urban water transit systems.

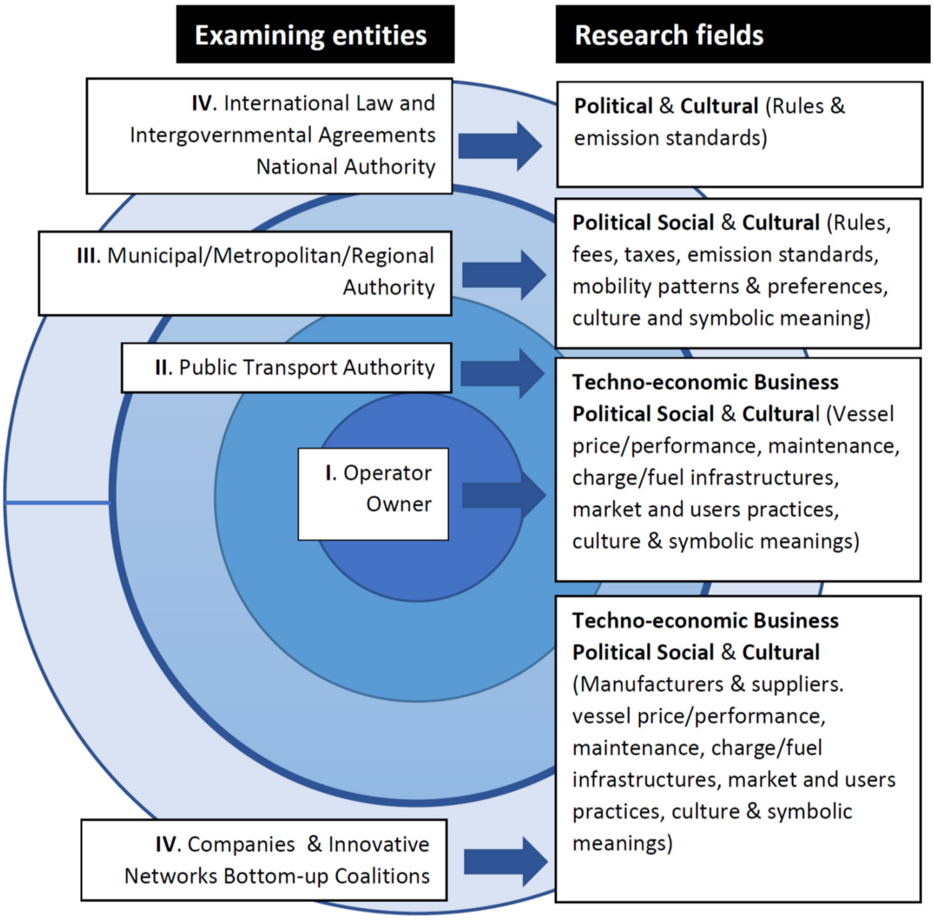

Figure 3. Stages of the research procedure.

In the system of profoundly combined operations/policy responsibilities, the three stages are usually referred to as one, most often public and monopolistic entities, while in systems with split responsibilities, a few public and private entities were subject to examination. Independent of the system structure, the first three research stages concern the constituents of sociotechnical regimes. On the margins of this central analysis, the roles of landscape (international or national rules and emission standards) and niche (business and/or civic coalitions) were the subject of review in the fourth research stage. The activity field of these bodies was potentially extensive—from strictly engineering issues to questions of quality of life (Figure 2). The primary sources of information were the websites of these entities or local press reports. The analysis of the grey literature was supported by reference to scientific articles, but the number of relevant works proved to be limited.

4. Results

A four stage research procedure allows identifying the implementation stage of each ferry system's electrification. It was verified whether electrification is planned or implemented. In both cases, the progress of these processes was analysed. Cities that have not yet taken significant action have also been identified. The conducted research also allowed to distinguish four groups of electrification drivers. Each of them played a significant role in at least a few cities.

4.1. Progress in Urban Water Transit Electrification

Activities in ferry systems' electrification were observed in 18 of the 24 cities (Table 1). All activities occurred since 2015. One city (Copenhagen) had accomplished the process: nine large scale implementations were in progress and five small scale ones. The initial activities—strategic planning or feasibility studies—were taking place in three cities.

Table 1. Progress in urban water transit electrification (as of mid-2021).

Location	System Size [1]	Stage of Implementation [2,3]	Year the First Vessel Was Introduced	Propulsion System	Retrofitted/New Built
Copenhagen	M	Accomplished	2020	Pure electric	New built
Stockholm	M	Large scale	2015	Pure electric/hybrid diesel–electric (fast-ferry)	Retrofitted/new built
Amsterdam	L	Large scale	2016	Hybrid diesel–electric/pure electric	Retrofitted/new built
London	L	Large scale	2018	Hybrid diesel–electric/pure electric	New built
Hamburg	M	Large scale	2018	Hybrid/plug in Hybrid diesel–electric	New built
Gothenburg	M	Large scale	2019	Plug-in hybrid diesel–electric	New built
Oslo	S	Large scale	2019	Pure electric	Retrofitted
Seattle	L	Large scale	2021	Plug-in hybrid diesel–electric	Retrofitted/new built
Lisbon	M	Large scale	2022	Pure electric	New built
Rotterdam	M	Large scale	2022	Pure electric/hybrid diesel–electric	New built
Venice	L	Small/large scale	2016/n.d.	Hybrid diesel–electric	New built/retrofitted
San Francisco	L	Small scale	2018/2021	Hybrid diesel–electric/pure electric (hydrogen fuel cells)	Retrofitted/new built
Hong Kong	L	Small scale	2020	Hybrid diesel–electric	Retrofitted
Wellington	S	Small scale	2021	Pure electric	New built
Stavanger	L	Small scale	2022	Pure electric (fast ferry)	New built
Auckland	L	Initial	Not applicable	Not applicable	Not applicable
Boston	S	Initial	Not applicable	Not applicable	Not applicable
Vancouver	M	Initial	Not applicable	Not applicable	Not applicable

[1] (**L**) large—more than seven lines and large number of stops; (M) medium—4–6 lines and a medium number of stops; (S) small—1–3 lines and a limited number of stops [19]. [2] No action—no official documented activities were reported; Initial——electrification was included in relevant strategies or feasibility studies were being carried out; Small-scale—prototype vessels were put into operation, but further plans did not include a modernisation schedule or are unofficial; Large-scale—the fleet was modernised, the first vessels are at least under construction or in operation, and there is an official plan to modernise the rest of the fleet; Accomplished—the fleet was successfully electrified. [3] No action: Brisbane (L), Istanbul (L), Izmir (L), New York (L), Rio de Janeiro (M), Sydney (L).

Significant variation in the choice of propulsion system was observed. The largest number (6) of cities have implemented or plan to implement two propulsion systems, due to the need to adapt to vastly different operating conditions (Amsterdam) or the different possibilities of ship owners, if there are several of them in a given city (Stockholm). Implementation may also be a consequence of rapid technological progress, which prompts ship owners to order new ships with the option of modernising their propulsion in the near future (Hamburg). Pure electric drive is being implemented in five cities and hybrid diesel–electric drive is planned in four cities. Two of them were plug in hybrid diesel–electric ships. In this system, diesel generators play a significantly smaller role (auxiliary or emergency). The vast majority of drives were installed on newly built ferries. Some cities, especially those with large ferry systems, decided to partially replace and modernise their fleets. Implementing electric drives only through modernisation is a pilot programme (Hong Kong) or applies only to modern units (Oslo).

The process of implementing electric drive systems does not have to cover all stages. As the example of Seattle shows, it is possible to omit the small scale implementation. The local Washington State Ferries (WSF) selected a comprehensive 20-year programme of the electrification of their entire fleet, starting immediately with the hybridisation of spare parts for ferries currently in use. While, in 2020, WSF operated 21 diesel powered ferries, in 2030 there will be only 14, while there will be 11 hybrid electric units. In turn, by 2040, these proportions will be 4 to 22 [62]. Most small scale modernisations are associated with research and development and with the challenges of using electric propulsion on fast ferries (Stavanger) or hydrogen fuel cells (San Francisco). Small scale development may also result simply from the small size of the system (Wellington).

The issue of cities where no official activity towards the electrification of ferry systems has been documented also requires clarification. The lack of evidence does not mean that the issue is being overlooked. It also does not mean that these cities are not taking steps towards carbon neutrality. As many as five out of six cities maintain large ferry systems. Their potential electrification is a considerable investment and organisational challenge. One barrier may be substantial investment in other, sometimes alternative, means of transport (Rio de Janeiro's BRT system and new diesel–electric ferries, or the bridges and tunnel across the Bosphorus Strait in Istanbul). Another barrier to electrification may be previous investment plans based on diesel drive or the use of fast ferries, for which mature technical solutions have not yet been developed (Brisbane or Rio de Janeiro). Other major cities (New York [63] and Sydney [64]) use emission reduction strategies, but do not directly focus on the electrification of ferry systems. They assume that the increase in the mass transit share in the transport modal split will reduce GHG emissions, regardless of the propulsion systems.

4.2. Drivers and Patterns of Electrification

4.2.1. Characteristics of the Systems

The systems' physical characteristics, resulting from natural, socioeconomic, and spatial conditions, significantly affect the electrification potential of urban water transit systems. The essential features are route and service type and the related technical and operational requirements. The degree of fleet modernisation and the age and level of the wear and tear of individual ships may also be substantial.

Three types of ferry routes were identified by Cheemakurthy et al. [19]. Type I represents linear routes along a river or water body connecting multiple destinations along the waterfront (Figure 4B). This type is conducive to transit orientated development—it maximises efficiencies and supports the economic development of waterfronts. Offering vessel speed competitive with other transport means is a challenge in this type of system. Type II was usually developed in the absence of land based transport connections. It is a simple river crossing with a two or three point stop configuration (Figure 4A). A short travel time and high frequency results in vessel design focused on quick turnaround and capacity. Type III refers to routes between the inner city and its suburbs (Figure 4C). The travel distance is significantly longer than types I and II, but the frequency is also much lower. Ferries should be more comfortable than capable, and economically viable in the long term.

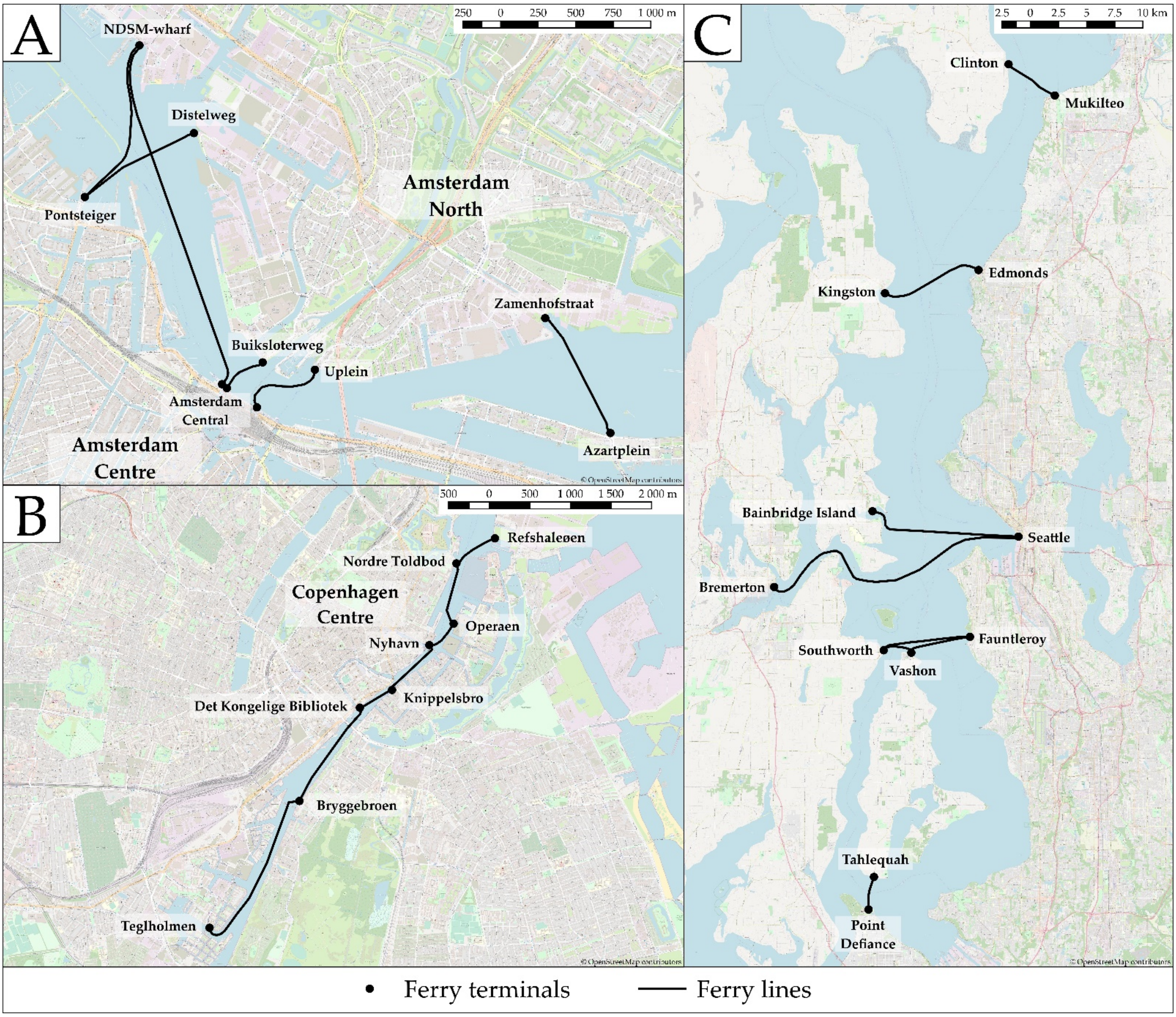

Figure 4. Types of ferry routes: (**A**) Amsterdam, (**B**) Copenhagen, (**C**) Seattle. Source: own elaboration based on OpenStreetMap data [65].

Route types I and II were primarily electrified in systems classified as accomplished or large scale. In the case of both types, the short stopping time is a challenge for battery charging. In Copenhagen (Damen E-Ferry 2306, with a length of 23 m and room for 80 passengers), a fully automated, fast charging system was applied. It repowers the battery packs (120 kWh) at both end stops of the I-type route in seven minutes. A similar solution was introduced to the Stockholm Movitz Ferry (length: 23 m, capacity: 100 passengers, battery capacity: 180 kWh). The other Stockholm ferry—Sjovagen (150 passengers)—has 500 kWh battery packs that are fully charged overnight, and partially twice a day. Lisbon, Gothenburg, and Hamburg were following the same development path. The latter two cities put or intend to put plug in hybrid diesel–electric ferries into service. The potential barrier to systems based on an electricity supply from the onshore grid is their expandability and power availability. In type II routes (Amsterdam or Woolwich–North Woolwich in London), hybrid diesel–electric systems were being developed. The travel range is short, but the passenger turnaround time is also short (type II ferries in Amsterdam need only about four minutes, while stops last two minutes). There is too little time to repower batteries with onshore chargers. Another advantage of hybrid diesel–electric systems is that there is no need to build an onshore charging facility. The common feature of the majority of the systems classified as ″accomplished″ or "large-scale" is the relatively small ferry length (30–40 m) and capacity (80–300 passengers), designed for navigation in sheltered waters (rivers or harbours). The high degree of fleet unification is the second distinguishing feature of this kind of ferry system. The existence of type III routes within urban water transit systems is not an obstacle to electrification. Although type III routes are not electrified first, technical solutions and modernisation plans are underway. The research and development of the E-ferry project proved that pure electric propulsion systems could ensure efficient ferry operation in coastal waters with a range of at least 40 km [66]. Seattle is a relevant example of type III route service development based on hybrid diesel–electric and, eventually (2040), plug in hybrid electric ferries. Due to coastal water conditions and transport demand, these ferries will be much larger (750–2020 passengers and 64–202 cars) [62]. Development works on fast ferries were also being carried out with the main aim of servicing type III routes. Stockholm is in the lead in this respect. Green City Ferry has been developing the BB Green concept since 2013 [67]. Candela offers a similar concept, the Candela P-30 [68]. Both concepts offer scalable passenger capacity (Candela offers capacities between 12–300 passengers), a pure electric propulsion system, cruising speeds of over 20 knots (twice as fast as a typical ferry), and low energy consumption per passenger.

Some systems' physical characteristics may substantially impede the electrification of an urban ferry fleet. The comparative case study revealed that the systems where no action has been taken consist of vessels of widely varying age, type, and size. This can hinder the search for the sociotechnical solution of electrification. In the case of Rio de Janeiro and Brisbane, an additional set of obstacles was identified. Firstly, the fleet was dominated by modern diesel–electric ferries with relatively low emission propulsion. Secondly, these vessels were fast ferries. The prospect of incurring further high costs for modernisation seems difficult to explain to the public, as is securing funding.

4.2.2. Local Climate and Transport Policies

The structure and role of public transport in cities, by its nature, depends on political activity: legislation, political strategies, and everyday politics. Political initiative is critical in the process of reconfiguring sociotechnical regimes. The analysis indicates the development of at least three types of policies are of crucial importance for the electrification of urban water transport systems (Table 2). So far, the most significant progress in electrification has been brought about by the urban carbon neutral policy. It is comprehensive—the electrification of ferries is only one element of the electrification of an entire transport fleet, most often busses. It is also used by large cities with extensive experience in implementing sustainable mobility and reducing GHG emissions. Copenhagen is an iconic example. By 2011, it had reduced CO_2 emissions by 21%, compared to 2005 [69]. The programme Transition to Electric Buses and Boats in Movia is electrifying the whole harbour bus fleet. It also initiated the replacement of the bus fleet with new electric busses [70]. These activities are expected to further significantly reduce GHG emissions by 2025. Amsterdam has taken remarkably similar steps, which are even more comprehensive. The electrification of the ferry and bus fleet is part of the much broader Smart City Mobility Concept programme, including a regenerative braking energy system for the metro trains and implementing an IT backbone for the smart mobility concept [71]. Both projects received grant support from the European Investment Bank as part of the European Local Energy Assistance (ELENA) project [72]. Urban transport and mobility are some of the third sectors supported in this program.

Table 2. Types of local policy involving urban water transit electrification.

Urban Policy Type	Main Features	Subtype Features	Most Relevant Locations
Urban carbon neutral policy	City authorities drive the electrification of all transport modes based on their experience in sustainable mobility; ambitious climate goals	Combined operations/policy responsibilities, external cofinancing	Copenhagen, Amsterdam, Hamburg, Lisbon
		Split operation/policy responsibilities	Stockholm
		Public–private partnership	Gothenburg
		Governmental green shipping policy	Oslo
Zero emissions waterborne transport policy	Waterborne transport strategies achieve general climate and transport goals	Driven by authorities	London, Seattle
		Bottom up networks	Auckland, San Francisco, Wellington
Research and development policy	Pilot developments as R&D projects (fast ferries, especially)		Venice, Stavanger

Both of the above cases represent a system with a high degree of combining operational activities with political responsibilities. When this link is weaker because of large numbers of operators, several individual projects are under process (Stockholm). In cooperation with the port authority, the local authority focusses on developing charging facilities—a public–private partnership (ElectriCity) fosters public transport electrification in Gothenburg [73]. On the other hand, strong national government support for green shipping distinguishes Oslo [74].

The second type is sectoral policy focussed on the modernisation of ferry systems. It may be carried out by entities responsible for this mode of transport, such as in Seattle, where the responsible entity is the Washington State Department of Transportation. WSF operates the most extensive ferry system in the USA, with 10 routes and 20 terminals in most of Seattle's metropolitan areas [62]. The sectoral policy may also be pursued by city authorities, e.g., in cooperation with port authorities. In London, the need to supplement the Mayor's Transport Strategy [75] with a programme dedicated to urban waterfronts was noted. London's Passenger Pier Strategy facilitates low emissions vessels and other transport options [76].

The electrification of ferry systems can also be stimulated from the bottom up, most often by innovative companies. In Auckland, a local ferry company formed a ferry system development strategy [77]. In turn, Wellington Electric Boat Building, in cooperation with a local ferry company, became involved in developing and constructing an electric ferry [78]. Two New Zealand companies—HamiltonJet and EV Maritime—intended to build advanced composite, battery powered commuter ferries with international markets in mind [79]. In California, on the other hand, Golden Gate Zero Emission Marine and Switch Maritime were developing the fuel cell vessel concept [80]. All these initiatives are linked to and supported by the public sector. For now, however, this support is more concerned with research and development than the mass implementation of electric vessels.

The development of electric ferries also proceeds through typical, formalised research and development projects. The best example is the projects granted by the EU Horizon 2020 Research and Innovation Programme. They are conducted within formalised networks which, in addition to research units, must consist of partners such as enterprises or municipal authorities. Stavanger is an excellent example of this development path. The TrAM consortium, consisting of research units, the maritime industry, and public authorities, were developing a zero emissions, fast-going passenger vessel through advanced modular production [81]. In turn, EU Horizon 2020 financed a technical and economic study of zero emission boats for public transport, inspired by the Venice passenger boat system [82].

4.2.3. Manufacturing Capacity and International Ferry Operators

A significant factor in the electrification of ferry systems may be innovative local enterprises from the maritime industry. As shown, for example, in Auckland, Wellington and California, the proximity of such entities is essential at the early stage of implementation. Local businesses know the operating conditions well and understand their customers' needs. Direct communication is also essential. The analysis of other cases also shows a relatively broad involvement of entities from a given urban region, or at least the same country, in the construction and modernisation of ferry systems. Out of the 24 systems, such co-location was observed in 17 cases. The possibility of commissioning the modernisation of a fleet to domestic, preferably local entities, provides additional economic (local development), political (voter support), and image (innovation) benefits.

The diffusion of innovation through entities operating in multiple markets may be potentially essential for the electrification of normative systems. One example would be Transdev, which was established in Gothenburg in 1922 but became an operator and global integrator of mobility over time. It supports 13 systems in five countries [83]. In Gothenburg, it is involved in the ElectriCity partnership, implementing electrical solutions in urban transport, including city ferry shipping. The experience gained in this project may facilitate the electrification of other systems operated by Transdev—for example, in Brisbane and Sydney.

4.2.4. Green City Branding

The theme of branding appears in the foreword to strategy and project documents, and the media discourse accompanying the electrification of ferry systems. On the one hand, cities with experience and success in this field—European Green Capitals—emphasise the electrification of urban transport, including ferries. Out of 10 cities assigned to the "accomplished" or "large-scale" stages, nine qualified for the European Commission's European Green Capital Award (EGCA). Five had received it: Stockholm (2010), Hamburg (2011), Copenhagen (2014), Oslo (2019), and Lisbon (2020). The actions these cities had taken do not appear to be merely a moral obligation. The European Commission recognises and rewards local efforts to improve not only the environment, but also the economy and the quality of life in cities [84]. These are crucial assets in talent, technology, and the tolerance of global urban competition [85]. Although the perspective of this particular award is European, numerous "green" rankings, despite significant differences in the structure of the set of criteria and results [86], usually also place cities in above average categories in global terms. Cities where the processes of electrification are not advanced also perceive the issue of their image. Public transport is often a showcase of the city for visitors, including tourists; it is a question of ordinary everyday experience. For this reason, one of the first electric passenger boats in Venice supposedly was directed to operate the line connecting the airport with the city.

5. Discussion

This study reduces the research gap in low carbon mobility transitions. The method used in this study helped to identify activities for the electrification of urban ferry systems in 24 coastal cities that have been documented in secondary qualitative data regarding the technical/economic performance reported by enterprises (ferry owners, operators, or manufacturers), policies developed by authorities (strategies and investment programmes), the scholarly literature, and professional media in the field. The results should be considered to contribute to scientific knowledge in urban sustainable mobility and shipping electrification. So far, research on urban ferry systems has not systematically addressed the issue of electrification. On the other hand, the research on the use of electric drives in shipping has treated urban waterborne transit marginally. However, the results should be treated as indicative because the experience of these cities is impossible to grasp in its entirety in a comparative case study (the scope vs. data availability trade off). Moreover, the process is vital—each quarter brings new reports on urban ferries system electrification.

Firstly, the study notes that most—18 out of 24—cities have started urban water transit electrification. According to general multi level dynamics [87], one case (Copenhagen) represents the mature phase (phase 4), wherein the new sociotechnical system replaces the previous one and becomes a new standard for city praxis. Nine cities are arenas of radical innovation diffusing into mainstream markets (phase 3). These cities have internalised the new sociotechnical landscape values and became powerful transition actors. Moreover, they are aware of price/performance improvements and economies of scale, and can seize the opportunity created by the emergent landscape to become more competitive. The remaining cities have transformed the innovation into the leading solution and deploy it in market niches (phase 2). The experimentation and learning activities (phase 1) focus on solutions (fast ferries or fuel cells). Cities need not start ferry electrification completely anew from scratch. In the case of five cities, proof of official activities in ferry electrification was not found. However, it is more a question of instrumental than discursive or structuralist resistance to low carbon transitions [88]. New and modern diesel powered ferries require to be amortised. Considering the introduction of the fjord ferry m/v Ampere in 2015, this prompted awareness that electric propulsion systems for ferries had become feasible [89], the shift in urban waterborne transit systems should be interpreted as significant.

Secondly, the research identified electrification patterns, especially those that have proven to be effective. It outlined three dominant transition pathways—a comprehensive carbon neutral policy, a transport industry policy, and a research and development policy. Each of them has been used successfully. However, in terms of the effects they have achieved, the first transition path seems to be the most promising. A comprehensive carbon neutral policy aims not only to electrify individual modes of transport. The pursuit of significant reductions in GHG emission does not preclude water transit systems, even if they are responsible for a negligible share of the emissions of the entire city. This kind of policy proved to be crucial for the shift in regimes, leading to the diffusion of radical innovation into mainstream markets. The interdependence between the degree of water transit electrification and a comprehensive sustainable policy becomes visible when comparing this study's results and the Deloitte City Mobility Index [90]. Most progressive cities in ferry system electrification also received high marks in the "environmental sustainability initiatives" sub-index. On the one hand, the results confirmed that large, global cities are trying to find practical solutions to the most crucial global problems [25,27,28]. On the other hand, the cities solved problems that they had generated by themselves [91]. Moreover, cities seize opportunities offered by the emergent sociotechnical landscape—the environmental policies of national governments. The domestic environmental performance index is far above the international average [92] in most cases. In light of the research by Tanko and Burke [42], the additional rationale for the policy becomes visible. Developing ferry systems is the answer, not only for commuting demand but also for fostering the economic development of revitalised waterfronts. The cases of London and Hamburg are significant examples of such an approach. To summarise the policy question, it is worth framing it by the "avoid–shift–improve" concept, to evaluate sustainable mobility policies [9]. Urban water transit electrification should result in a "shift" in modal split towards public transport modes and should "improve" vessel energy efficiency. For obvious reasons, it does not contribute to the "avoidance" of travel, which is one of the features of the sustainable mobility paradigm [93].

Thirdly, systems' physical characteristics determine the electrification patterns. However, the introduction of hybrid diesel–electric or electric ferries is possible even for the longest routes. Atypical solutions that are well suited to the conditions of individual cities remind us that transitions to carbon neutrality must be understood as a spatially constituted process [9,60]. The diversity of electric solutions introduced in the cities under study emphasises the recombinant innovations in the technological transition. As Frenken et al. stated [94], "innovation effort in a society has the biggest impact on technological progress when it is just large enough to create new varieties that subsequently can be fused through recombinant innovation triggering a technological transition". In this approach, cities can be considered a bridge between niches and regimes that provide the actual conditions for implementing sociotechnical configurations [59].

Fourthly, the role of multimarket companies—such as Transdev—seems to be engaging in the context of a shift in sociotechnical regimes. The successful electrification accomplished by a single market company, at most, supports the emerging sociotechnical landscape. It becomes the "best practice" for others. In the case of a multi-market company, the possibility of diffusing horizontal innovation between markets appears. In the analysed cases, the question of city branding plays an essential role in ferry electrification. The impact of receiving the EGCA is significant. However, as Sareen and Grandin argued [95], there is a risk that the efforts stimulated by the award competition optimise local sustainability effects with no regard for larger cross scale or global repercussions.

Setting the scope of analysis to local patterns and the consequences of electrification is a significant limitation of this study. The development of new propulsion systems for ferries brings cities noticeable discursive and material benefits. Instead of avoiding a negative environmental impact, they may relocate it outside the city (energy production or ferry manufacturing related emissions). The next question is difficulty in finding the manifestations of incumbent regimes' resistance to low carbon transition. They are obscured by the dominant sustainability agenda and discourse. Finally, the outcomes of comparative case analysis result from the depth–scope trade off. It depends not only on research design, but also on limitations in online access to transit operators' official websites, transport planning policy or strategies, and technical reports, which are primarily published in English.

6. Conclusions

City activities, also including urban mobility, play a crucial role in climate change mitigation. Urban mobility is currently at a crossroads. In a business as usual scenario, urban transport CO_2 emissions will grow by one fourth by 2050. Nevertheless, during this period, it may drop by about one third. To make the drop happen, we need to introduce comprehensive policies and measures. The electrification of urban transport is one feasible solution. This study investigates whether and how the electrification of urban water transit systems has occurred—a means of transport that has not been well researched in this respect. The general outcome is that urban electric passenger ferries left their market niches and triggered a radical innovation diffusion into mainstream markets. However, urban diversity results in various electrification paths, such as an urban carbon-neutral policy, a zero emissions waterborne transport policy or a research and development policy. This outcome has policy implications for urban stakeholders and policymakers. Electric propulsion systems will become better and more affordable. They will, therefore, become difficult for policymakers to ignore. Stakeholders and policymakers should investigate emerging technical solutions and should choose the most relevant one for their urban conditions, demand, and political promises. Two general premises, in particular, need thorough consideration: coordinating water transit electrification and development while modernising a whole urban transport system in line with sustainable mobility requirements, and accounting for the total impact of these activities for improving cross scale or global sustainability.

This study also yields directions for future research. Firstly, investigating the following cases rooted in the different environmental, socioeconomic, and political conditions reveals new electrification patterns and enriches the body of comparative studies. Secondly, further studies on citizens, stakeholders, and policymakers help in understanding the motives and aims of electrification activities. This is essential in the case of investigating barriers and resistance to transitions. Thirdly, an assessment of electrification outcomes for sustainability going beyond the city or urban region territory is needed.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The author would like to thank Krystian Puzdrakiewicz, MA for the visual design of the map.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Entities responsible for system organization, operations, and maintenance were recognized as core actors that may shift ferry systems towards electrification. Depending on the country's administrative division and local power architecture, core actors are usually private companies, public companies, or public authorities—local, metropolitan or regional (Table A1). Each entity examination included: analysis of the condition of the ferry fleet, in particular, the use of pure electric or hybrid diesel–electric vessels; the fleet's susceptibility to modernization; the entity's attitudes towards environmental protection; and fleet modernization plans. Connections' spatial patterns, infrastructural resources, passenger facilities were also taken into account.

Table A1. The list of core actors responsible for the shift towards electrification.

Location	Name of entity	Website
Amsterdam	GVB	Welcome to GVB ∣ GVB. Available online: https://en.gvb.nl/# (accessed on 11 April 2021).
Auckland	Fullers 360 Experiences & Cruises	Fullers 360—Experiences & Cruises ∣ Auckland, New Zealand. Available online: https://www.fullers.co.nz/ (accessed on 21 March 2021).
Boston	Massachusetts Bay Transportation Authority	MBTA—Massachusetts Bay Transportation Authority. Available online: https://www.mbta.com/ (accessed on 22 March 2021).
Brisbane	Brisbane City Council	CityCat, SpeedyCat and ferry services ∣ Brisbane City Council. Available online: https://www.brisbane.qld.gov.au/traffic-and-transport/public-transport/citycat-and-ferry-services (accessed on 21 March 2021).
Copenhagen	Trafikselskabet Movia	Movia. Available online: https://www.moviatrafik.dk/ (accessed on 18 March 2021)
Gothenburg	Västtrafik	Västtrafik AB: public transport in Västra Götaland. Available online: https://www.vasttrafik.se/en/ (accessed on 23 March 2021)
Hamburg	HADAG Seetouristik und Fährdienst	HADAG Hamburg—home. Available online: https://hadag.de/en/ (accessed on 25 March 2021)
Hong Kong	Transport Department.	Transport Department—Ferries. Available online: https://www.td.gov.hk/en/transport_in_hong_kong/public_transport/ferries/index.html (accessed on 25 March 2021).
Istanbul	Şehir Hatları	Şehir Hatları A.Ş. Available online: http://en.sehirhatlari.istanbul/en (accessed on 25 March 2021).
Izmir	İzdeniz	Izmir Deniz Işmetliciligi A.Ş. Available online: https://www.izdeniz.com.tr/en/ (accessed on 25 March 2021).
Lisbon	Transtejo Soflusa	Soflusa Transtejo ∣Between the banks of the Tagus. Available online: https://ttsl.pt/ (accessed on 12 April 2021).
London	Transport for London	Keeping London moving—Transport for London. Available online: https://tfl.gov.uk/ (accessed on 27 March 2021).
New York	NYC Ferry	NYC Ferry ∣ NYCEDC. Available online: https://edc.nyc/project/nycferry (accessed on 27 March 2021).

Oslo	Ruter	About us ǀ Ruter. Available online: https://ruter.no/en/about-ruter/about-us/ (accessed on 28 March 2021).
Rio de Janeiro	CCR Barcas	CCR Barcas—É por aqui que a gente chega lá. Available online: https://www.grupoccr.com.br/barcas/ (accessed on 28 March 2021).
Rotterdam	Waterbus	Homepage—Waterbus. Available online: https://www.waterbus.nl/en (accessed on 2 April 2021).
San Francisco	San Francisco Bay Area Water Emergency Transportation Authority	WETA Home ǀ Water Emergency Transportation Authority. Available online: https://weta.sanfranciscobayferry.com/ (accessed on 2 April 2021).
Seattle	Washington State Department of Transportation	Washington State Department of Transportation. Available online: https://wsdot.wa.gov/ (accessed on 2 April 2021).
Stavanger	Kolumbus	Kolumbus AS—public transport in Rogaland. Available online: https://www.kolumbus.no/en/ (accessed on 28 March 2021).
Stockholm	SL	In English ǀ SL. Available online: https://sl.se/en/in-english (accessed on 3 April 2021).
Sydney	Transdev Sydney Ferries	Discover, Experience, Share Sydney Harbor by Ferry. Available online: https://www.beyondthewharf.com.au/ (accessed on 21 March 2021)
Vancouver	TransLink	Home ǀ TransLink. Available online: https://www.translink.ca/en (accessed on 4 April 2021)
Venice	Azienda del Consorzio Trasporti Veneziano	ACTV ǀ Muoversi a venezia. Available online: http://actv.avmspa.it/en (accessed on 5 April 2021)
Wellington	East by West Ferries	East by West Ferries ǀ Wellington's unique harbour ferry. Available online: https://eastbywest.co.nz/ (accessed on 5 April 2021)

Appendix B

Potentially, there were several types of strategic documents fostering the electrification of urban water transit systems. Starting with the most general ones, ending with the most focused on ferry shipping, these could have been the following documents: general development strategy, carbon neutral strategy/resilience strategy/climate action plan, mobility/transport strategy or mid/long term plan, harbor/waterfronts development strategy, urban water transit development/modernization strategies/programs/plans. The strategic documents were examined for each location to find content related to the ferry system, with particular attention to its electrification. Each location's most relevant document helps define the nature and scope of policy support for the local water transit system. Selected documents were analyzed regarding the importance of ferries electrification, recognition of local requirements and technical conditions of electrification, the degree of specificity of the proposed activities and advancement in their implementation, knowledge of costs and securing sources of financing. Table A2 contain the set of crucial analyzed documents. From the article objectives' point of view, the most important of them were referred to in the main text.

Table A2. The list of key strategic documents on ferry system electrification.

Location	Document
Amsterdam	*New Amsterdam Climate. Roadmap Amsterdam Climate Neutral 2050*; Amsterdam, 2020;
Auckland	Gulf 2025: A New Strategy to Improve Auckland's Ferry Network. Available online: https://www.gulf2025.co.nz/ (accessed on 19 July 2021).

Boston	*Inner Harbor Connector. Business Plan for New Water Transportation Service*; Boston, 2019;
Brisbane	*Transport Plan for Brisbane—Strategic Directions*; Brisbane, 2018;
Copenhagen	*CPH 2025 Climate Plan. A Green, Smart and Carbon Neutral City*; Copenhagen, 2012;
Gothenburg	*Gothenburg 2035 Transport Strategy for a Close-Knit City*; Gothenburg, 2014;
Hamburg	*HADAG announces details of its fleet renewal program*; Hamburg, 2019;
Hong Kong	*Hong Kong's Climate Action Plan 2030+*; Hong Kong, 2017;
Istanbul	*2014—2023 Istanbul Regional Plan*; Istanbul, 2016;
Izmir	*Izmir Public Transport Master Plan*, Izmir, 2017;
Lisbon	*Roadmap for Carbon Neutrality 2050. Long-Term Strategy for Carbon Neutrality of the Portuguese Economy by 2050*; Lisbon, 2019;
London	*London's Passenger Pier Strategy. A safe, sustainable and integrated pier network for London*; London, 2019;
New York	*OneNYC 2050 Building a Strong and Fair CITY. Efficient Mobility*; New York, 2019;
Oslo	M2016—Ruter's long term strategic mobility plan. Available online: https://m2016.ruter.no/en/ (accessed on 28 March 2021).
Rio de Janeiro	*Resilience Strategy of the City of Rio de Janeiro*; Rio de Janeiro, 2016;
Rotterdam	*Smart Accessibility for a Healthy Economically Strong and Attractive Rotterdam. Rotterdam Urban Traffic Plan 2017–2030+*; Rotterdam, 2017;
San Francisco	*The San Francisco Bay Area Water Emergency Transportation Authority's Strategic Plan*; San Francisco, 2016;
Seattle	*Washington State Ferries. System Electrification Plan*; Seattle, 2020;
Stavanger	*Climate and Environmental Plan 2018–2030*; Stavanger, 2018;
Stockholm	*Strategy for a Fossil-Fuel Free Stockholm by 2040*; Stockholm, 2016
Sydney	*Future Transport Strategy 2056*; Sydney, 2020;
Vancouver	Transport 2050. Available online: https://www.transport2050.ca/ (accessed on 4 April 2021)
Venice	Scarpa, C., Towards Venice Climate Action Plan. Available online: https://eurocities.eu/wp-content/uploads/2020/11/speednetworking_Venice_presentation3.pdf (accessed on 6 April 2021)
Wellington	*Wellington Urban Growth Plan*; Wellington, 2015.

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